Optimal Generation Scheduling with Operating Reserves including Wind Uncertainties

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***Abstract*— The increase in the production cost of electricity from conventional energy sources, led systems to look for cheaper and cleaner energy sources like wind and solar. Over past few years wind energy integration drew more attention in the electricity markets. But, due to uncertainties in wind energy forecasts and to maintain system under balance condition, additional services are required. Such additional services are named as Ancillary Services. This paper presents a scheduling methodology for thermal generators, under wind integration uncertainties to serve the demand, while providing a schedule for operating reserve (Ancillary Services). In this paper minimization of Operating cost objective is considered which includes thermal units fuel cost and cost paid to reserve, required due to intermittency in wind energy forecast. The uncertainties in wind are also considered, wind output is modelled using weibull probability density function (PDF). Dynamic Programming method with Priority-list is used to schedule thermal units. The performance and feasibility of the projected method is illustrated with case studies on 6 and 10 thermal generators test systems, along with one wind generator is considered and results are found encouraging.**

Keywords—Renewable energy, Wind, Ancillary services, Dynamic Programming, Priority list method, Unit Commitment, Reserves.

NOMENCLATURE

$Pt_{i,t}$	Power generated from committed generator i in hour t
$Cg_i(.)$	Cost function of generator i
$Cr_i(.)$	Cost function of generator i providing reserve
$Ptr_{i,t}$	Power generated from committed generator i to provide reserve in hour t
Pw_t	Power generated from wind turbine in hour t
a_i, b_i, c_i	Cost coefficients of thermal generators
br_i	Cost coefficient of reserve provision by thermal units
$U_{i,t}$	Thermal generators status in hour t
Ng	Total no of generators
Pd_t	Demand in time t
R_t	Reserve required in hour t
WR_t	Reserve required due to Wind intermittency
$Ptmax_{i,t}$	Maximum installed capacity of thermal unit *i* at hour *t*
$Ptmin_{i,t}$	Minimum possible generation of thermal unit *i* at hour *t*.
P.C	Production cost
R.C	Reserve cost

I. INTRODUCTION

Growing concern over climatic changes and sustainability have led the modern power systems to seek the integration of electricity derived from renewables. Among such green resources, wind generation and its integration has grown significantly, and further growth is forecasted in future. Intermittency of wind power becomes a functional issue. So, In order to maintain system stability the impact of wind power integration and dispatch in to the system should be evaluated [1]. Restructured electricity markets like Electric Reliability Council of Texas (ERCOT), EIRGRID (Ireland), Australian National Electricity Market, enabled bidding for both energy and ancillary services competitively. In those ISO's ancillary services bidding has evolved similar to energy bidding. The ISO by considering market constraints dispatch's both ancillary services bids and energy bids [2]. It is practiced in these markets to have a reserve capacity equal to the largest available thermal generator or 5-10% of peak load demand.

In [3] energy and spinning reserve markets were cleared by using a security constrained market clearing mechanism.By using both spot market and bilateral contracts energy is dispatched by considering consumer participation. However Spinning reserve cost was not considered. A market was developed in [4] for spinning reserve ancillary service dispatch competitively. This market is dispatched to alleviate the total payments towards spinning reserve. In [5] an optimal scheduling strategy for Spinning Reserve services was proposed. Features of probabilistic approaches for spinning reserve assessment were reported in [6-8]. Under the integration of wind power into the electricity grid, the procurement of Ancillary services draws more attention in protecting the system balance. When Wind generation is added, power system will need additional regulation, load-following, reactive power and spinning reserve from the rest of the generators. The optimal generation mix will fluctuate with the amount of wind integrated into the system [9]. Simultaneous energy and Reserve allocation is essential in Wind integration. [10] Summarized the salient points in wind Integration. In [11] to find the wind ramp events an optimal dynamic programming method was proposed. To incorporate intermittency and unpredictability of wind into the unit-commitment problem a hybrid dynamic programming method is proposed in [12]

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In [13] Impact of wind power which is modelled using wind speed time series is analyzed by security constrained economic dispatch to interpret Intermittency of wind power for scheduling and dispatch of thermal generators. [14] presented the optimum security constrained scheduling of thermal and gas generators to handle Wind generators by using Fuzzy Mixed integer linear Programming. In order to maintain system security and reliability, reserves as ancillary services have been purchased centrally by ISO. A weibull PDF method to model the uncertainties in the wind forecasts in Economic Dispatch is presented in [15]. This paper presents a unit commitment schedule, with which market participants have to operate optimally their generators to meet load and reserve requirement under wind uncertainties. In order to meet mismatches in load and generation operating reserves are considered to raise the generation output. Less than one hour schedules is beyond the scope of this paper. The work investigates the energy and operating schedule problem. In order to minimize the cost associated with energy and operating reserve a scheduling strategy that has been developed in this paper. Priority list based unit commitment method for identifying the optimal solution is used. Different case studies were done on 6 unit and 10 unit test systems in order to validate the results of the proposed method.

The paper is organized as : Section I gives introduction and literature survey. Section II deals with the problem formulation. Section III details algorithm for the proposed method. Section IV describes modelling of wind Energy forecasting. Section V presents outcomes of the work and discussions. Finally, Section VI provides contributions of the work with concluding remarks.

II. Mathematical Modelling

Unit-commitment is an algorithm used to schedule the generation, while meeting the load demand and reducing the net operating cost. This section presents mathematical modelling of scheduling of generating units with wind integration to the grid. Wind with its variable nature poses many problems in daily scheduling of the generators, that are related to security of the system. This paper attempts to consider the Intermittency of the wind and gives the solution for a unit scheduling of the thermal generators and reserve requirement for 24 hours.

$$\text{Operatingcost} = \min\left[\sum_{t=1}^{T}\left[\sum_{i=1}^{N_g}[Cg_i(Pt_{i,t}) + Cr_i(Ptr_{i,t})]\right]\right] \quad (1)$$

Where

$$Cg_i(Pt_{i,t}) = a_i + b_i * Pt_i + c_i Pt_i^2$$

$$Cr_i(Ptr_{i,t}) = br_i * Ptr_i$$

Subjected to constraints

Power Balance constraint

$$\sum_{i=1}^{N_g}(U_{i,t} * Pt_{i,t}) + Pw_t = Pd_t \quad (2)$$

Reserve requirement constraint

$$\sum_{i=1}^{N_g} U_{i,t} * Ptr_{i,t} \geq R_t + WR_t \quad (3)$$

Thermal Unit constraint

$$Pt\min_{i,t} \leq Pt_{i,t} + Ptr_{i,t} \leq Pt\max_{i,t} \quad (4)$$

Where

$$U_{i,t} = \begin{cases} 1 & \text{UnitON} \\ 0 & \text{UnitOFF} \end{cases}$$

III. Algorithm

The algorithm for the proposed wind, Reserve scheduling is as follows:

Step 1) Read all system data and forecasted wind power.

Step 2) Find order in which the units should be turn ON by priority list method.

Step 3) Calculate system reserve requirements of hour t.

Step 4) Find the load to be served by the thermal units by using simplified dispatch

Step 5) Check t<24? Yes, go to Step 2; otherwise, go to Step 6.

Step 6) By using Economic dispatch recalculate the accumulated costs of saved hours.

Step 7) Check whether all the constraints are satisfied?

If yes, go to next step; otherwise, go to Step 2.

Step 8) Print the Optimal Unit Commitment schedule and cost of reserves.

IV. Modelling of Uncertainties in Wind Energy Forecasting

A. Forecasting of Wind Energy

The variability and uncertain nature of the wind needs more attention towards its integration to the grid. In the large scale wind farms integration, forecasting plays a crucial role. And also due to uncertainty of wind forecasting Operating Reserve requirement also increases. So a method in order to estimate wind profile accurately is needed. Weibull probability density function (PDF) [16] for better accuracy in wind forecasting is used by many researchers. In order to evaluate the reserve requirement, PDF for wind power output is assumed. The historical daily wind speed data was collected from EirGRID (Ireland transmission system operator).

The complete information of wind speed is described by weibull probability density function, which is given by eq. (5) [17].

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \quad (5)$$

Where k is called the shape parameter, and c is called the scale parameter. The wind speed distribution for the considered data is given in fig.1. The mean velocity value for the data period was $v_{mean} = 5.53 m/s$ weibull factor $c = 6.16 m/s$ and $k = 3$. Here wind is considered to be always blowing.

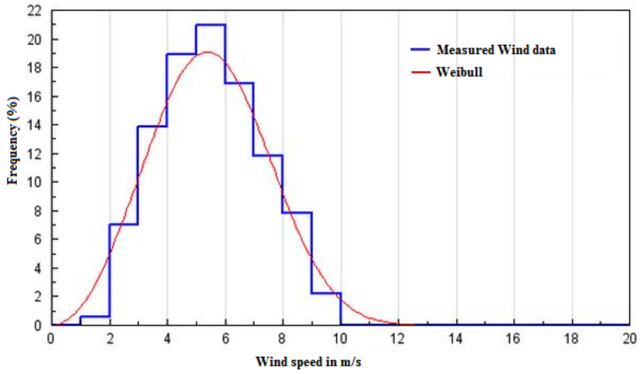

Fig. 1. wind speed distribution

Enercon E-48 (810kw) wind turbine is considered in this studies. The design parameters of a wind turbine like cut-in speed, rated speed and cut-out wind speeds are considered as 2 m/s, 14 m/s, and 25 m/s, respectively. Power output Pw_t of the wind turbine is given in the eq. (6).

$$Pw_t = \begin{cases} 0 & \text{for } v_t < v_i \text{ and } v_t > v_{out} \\ \mathrm{P_t}\left(\dfrac{v_t - v_{in}}{v_{ra} - v_{in}}\right) & \text{for } v_{in} \le v_t \le v_{ra} \\ \mathrm{P_t} & \text{for } v_{ra} \le v_t \le v_{out} \end{cases} \quad (6)$$

Where v_t is the wind speed in m/s, v_{ra} rated wind speed, v_{in} cut-in speed and v_{out} cut-out speed.

The wind power output can be modelled into two parts Continous between $v_{in} \le v_t \le v_{ra}$ eq. (7) and Discrete between $v_t < v_i$ and $v_t > v_{out}$ and $v_{ra} \le v_t \le v_{out}$ eqs. (8) and (9) [18].

$$f_w(P) = \frac{khv_{in}}{P_t c}\left[\frac{1+\frac{h*P}{P_t}v_{in}}{c}\right]^{k-1} x\exp\left[-\left(\frac{1+\frac{h*P}{P_t}v_{in}}{c}\right)^{k}\right] \quad (7)$$

The discrete range wind power output can be given as the probability of event P=0 is

$$P_t(P=0) = P_t(v_t < v_{in}) + P_t(v_t > v_{out})$$
$$= 1 - \exp\left[-\left(\frac{v_{in}}{c}\right)^{k}\right] + \exp\left[-\left(\frac{v_{out}}{c}\right)^{k}\right] \quad (8)$$

The Probability of event P=P_t is

$$P_r(P = P_t) = P_t(v_{ra} \le v_t \le v_{out}) = \exp^{-\left[\frac{v_{ra}}{c}\right]^{k}} - \exp^{-\left[\frac{v_{out}}{c}\right]^{k}} \quad (9)$$

The sum of these two probalities of occuring in the wind power modelling is 1.

B. The forecasted wind power with weibull PDF method.

Fig. 2 shows the wind power curve of wind turbine. The Rotor diameter of the turbine is 48m and capacity factor 22%.

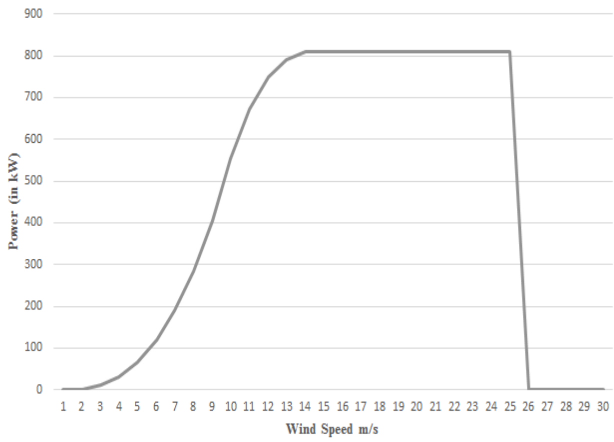

Fig. 2. Power curve of a Enercon E-48 810kW wind turbine

The Power output of wind form consisting several of Enercon E-48 turbines with total installed capacity of 100 MW over a period of 300 hrs is given in the Fig. 3. Fig. 4 gives the comparison between ANN wind power forecast and weibull PDF method. It is evident from Fig. 4 that the total reserve requirement is reduced in Weibull PDF method.

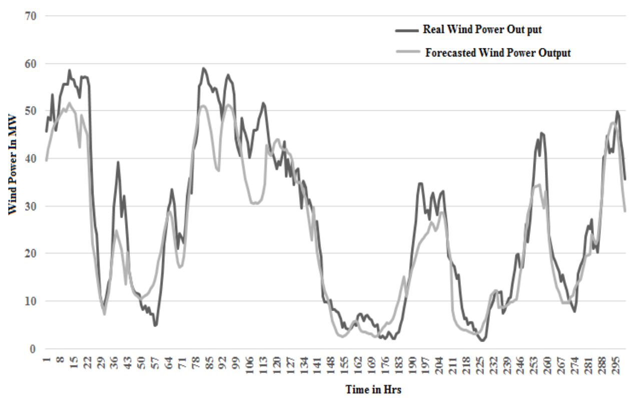

Fig. 3. Forecasted power out from the 100 MW Wind Form.

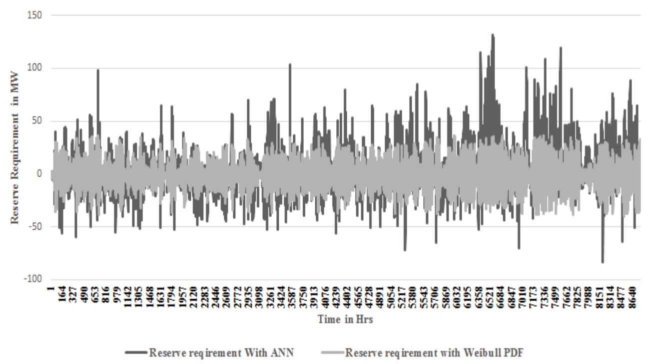

Fig. 4. Reserve requirement for the Weibull PDF method

V. CASE STUDY

TABLE I. IEEE 30 BUS 6 GENERATOR DATA

Units	*a* *($/hr)*	*b* *($/MWhr)*	*C* *($/MW²hr)*	*Ptmin* *(MW)*	*Ptmax* *(MW)*	*br* *($)*
1	0	2	0.0037	50	200	4.48
2	0	2.75	0.0175	20	80	6.55
3	0	1	0.0625	15	50	8.25
4	0	3.25	0.0083	10	35	4.83
5	0	3	0.025	10	30	5.5
6	0	3	0.025	12	40	6.21

TABLE II. DEMAND FOR IEEE 30 BUS SYSTEM ALONG WITH WIND POWER OUTPUT OF 100MW WIND FARM

Hours	*Demand (MW)*	*Wind (MW)*	*Hours*	*Demand (MW)*	*Wind (MW)*
1	231.4	39.7	13	305.2	47.6
2	220.8	42.8	14	304.8	41.6
3	206.4	45.2	15	294	48.6
4	197.6	46.8	16	292.4	46.9
5	192.1	48	17	293.9	43.4
6	196	49	18	299.7	33.3
7	201.5	49.9	19	309	23.7
8	238	50.8	20	303.9	18.1
9	285.3	50.5	21	308.8	14.3
10	300.6	51.7	22	312.6	11.4
11	305.3	50.7	23	282.6	8.3
12	304.9	50.1	24	247.5	8.4

A. 6 Unit System

Case 1: Without Wind Generator

To illustrate the merits of the proposed method IEEE 30 bus test system with six thermal units is taken. Here 10% operating Reserve service is considered. Table I gives system characteristics and Table II gives the load and wind output data. Table III illustrates the Unit commitment of the 6 generators without the integration of wind energy. The total operating cost obtained in this case is $ 22,432.

TABLE III. UNIT COMMITMENT OF IEEE 30 BUS SYSTEM WITH 10 % RESERVE

Hrs	*Unit 1 (MW)*	*Unit 2 (MW)*	*Unit 3 (MW)*	*Unit 4 (MW)*	*Unit 5 (MW)*	*Unit 6 (MW)*	*P.C ($)*	*R.C ($)*
1	174.4	20	18.3	24.4	10	12	624	132
2	172.2	20	18.2	14.8	10	12	590.4	124
3	161.6	20	17.6	10	10	12	546.3	116
4	152.3	20	17	10	10	12	520	111
5	146.4	20	16.7	10	10	12	503.8	108
6	150.6	20	16.9	10	10	12	515.4	110
7	156.5	20	17.3	10	10	12	531.8	114
8	175.7	20	18.4	30.4	10	12	645.4	137
9	200	30	22.4	35	16	16	801.5	199
10	200	36.5	24.2	35	20.5	20.5	854.7	230
11	200	38.5	24.8	35	21.9	21.9	871.6	234
12	200	38.2	24.7	35	21.8	21.8	869.7	233
13	200	38.3	24.7	35	21.8	21.8	870.7	232
14	200	38.2	24.7	35	21.7	21.7	869.2	232
15	200	33.7	23.4	35	18.6	18.6	831.4	220
16	200	33	23.2	35	18.1	18.1	826.1	216
17	200	33.6	23.4	35	18.6	18.6	831.2	220
18	200	36.1	24.1	35	20.2	20.2	851.3	229
19	200	39.9	25.2	35	23	23	884.6	236
20	200	37.8	24.6	35	21.5	21.5	866.4	232
21	200	39.9	25.2	35	22.9	22.9	884.2	236
22	200	41.5	25.6	35	24	24	898.3	239
23	200	28.9	22.1	35	15.2	15.2	792.5	193
24	181.4	20	18.7	35	10	12	676.2	141
TOTAL OPERATING COST(P.C+R.C)							**22,432 $**	
TOTAL RESERVE COST(R.C)							**4475 $**	

Case 2: With a Wind Generator

In this case, the same six units are considered along with a wind generator. The maximum capacity of the wind generator is considered to be 100MW. The operating cost of the wind turbine is considered to be negligible. The operating cost obtained in this case is $ 19,728.6. Table IV illustrates the Unit commitment of the 6 generators along with wind with no Intermittency.

TABLE IV. UNIT COMMITMENT OF IEEE 30 BUS SYSTEM WITH 10 % RESERVE AND 100 MW WIND TURBINE

Hrs	*Unit 1 (MW)*	*Unit 2 (MW)*	*Unit 3 (MW)*	*Unit 4 (MW)*	*Unit 5 (MW)*	*Unit 6 (MW)*	*P.C ($)*	*R.C ($)*
1	150.5	20	16.9	10	10	12	505.6988	132
2	136.4	20	16.1	10	10	12	471.3623	124
3	118.9	20	15	10	10	12	426.2621	116
4	107.5	20	15	10	10	12	397.3597	111
5	100.2	20	15	10	10	12	379.265	108
6	103.5	20	15	10	10	12	387.0626	110
7	108.8	20	15	10	10	12	399.4651	114
8	147	20	16.7	10	10	12	488.0338	137
9	176.2	20	18.4	32.4	10	12	647.6939	199
10	188.8	20	19.2	35	10	12	689.1531	230
11	194.7	20	19.5	35	10	12	707.87	234
12	194.8	20	19.5	35	10	12	708.8026	233
13	197.3	20.3	19.7	35	10	12	719.5001	232
14	200	22.1	20.2	35	10.5	12	737.6217	232
15	184.7	20	18.9	35	10	12	678.4518	220
16	184.7	20	18.9	35	10	12	679.8109	216
17	189.6	20	19.2	35	10	12	695.874	220
18	200	23.4	20.6	35	11.4	12	748.4176	229
19	200	31.1	22.7	35	16.8	16.8	813.8022	236
20	200	31.1	22.7	35	16.8	16.8	815.5856	232
21	200	34.5	23.7	35	19.2	19.2	847.3257	236
22	200	37.2	24.4	35	21	21	872.7396	239
23	200	25.8	21.2	35	13	13	780.784	193
24	176.1	20	18.4	32.2	10	12	655.6558	141
TOTAL OPERATING COST(P.C+R.C)							**19,728.6 $**	
TOTAL RESERVE COST(R.C)							**4475 $**	

Case 3: Ten-Unit Thermal System with a Wind Generator considering Intermittency and reserve requirement

Along with case 2, 20% Intermittency is considered in Wind generation forecast, Reserve requirement is also considered in this case. Table V illustrates the Unit commitment of the 6 generators along with wind power out modelled using Weibull PDF method. The operating cost obtained in this case is $ 23,663.75.

TABLE V. UNIT COMMITMENT OF IEEE 30 BUS SYSTEM WITH 10 % RESERVE AND 100MW WIND TURBINE WITH INTERMITTENCY

Hrs	*Unit 1 (MW)*	*Unit 2 (MW)*	*Unit 3 (MW)*	*Unit 4 (MW)*	*Unit 5 (MW)*	*Unit 6 (MW)*	*P.C ($)*	*R.C ($)*
1	169.3	20	18	10	10	12	567.985	225.074
2	156.6	20	17.3	10	10	12	535.7465	224.872
3	140.3	20	16.3	10	10	12	491.1489	222.979
4	130.2	20	15.7	10	10	12	462.7377	218.548
5	123.8	20	15.3	10	10	12	445.1125	216.144
6	127.5	20	15.5	10	10	12	455.0607	221.826
7	132.9	20	15.9	10	10	12	469.6485	229.535
8	171	20	18.1	10	10	12	568.1136	255.775
9	197.3	20.3	19.7	35	10	12	731.7792	318.348
10	200	26.8	21.5	35	13.8	13.8	776.677	375.779
11	200	29	22.1	35	15.3	15.3	794.4729	388.113
12	200	28.9	22.1	35	15.2	15.2	793.994	384.359
13	200	29.5	22.3	35	15.6	15.6	800.2873	378.637
14	200	30.4	22.5	35	16.3	16.3	808.9773	364.273
15	200	24.6	20.9	35	12.2	12.2	760.317	348.744
16	200	24.3	20.8	35	12	12	759.012	339.481
17	200	25.6	21.2	35	12.9	12.9	769.2148	341.332
18	200	29.9	22.4	35	15.9	15.9	805.89	335.091
19	200	35.5	23.9	35	19.9	19.9	857.3179	311.173
20	200	34.5	23.6	35	19.1	19.1	848.434	288.853
21	200	37.2	24.4	35	21.1	21.1	874.4518	281.861
22	200	39.3	25	35	22.5	22.5	894.6517	274.903
23	200	27.4	21.7	35	14.1	14.1	795.7046	220.308
24	177.4	20	18.5	35	10	12	669.3404	161.666
TOTAL OPERATING COST(P.C+R.C)							**23,663.75 $**	
TOTAL RESERVE COST(R.C)							**6927.67 $**	

The results are compared with Artificial Neural network (ANN) based wind forecast method and results are tabulated in table VI. 300 patterns are considered from March 2009 to April 2010 wind data from EirGRID. ANN network is trained using hour of the day, wind speed.

TABLE VI. COMPARISON OF RESERVE COST

Method	Reserve cost (case 3) ($)
ANN	**10338.79**
Weibull PDF	**6927.67**

B. 10 Unit System

TABLE VII. DEMAND FOR 10 UNIT SYSTEM ALONG WITH WIND POWER OUTPUT OF 250 MW WIND FARM

Hours	*Demand (MW)*	*Wind (MW)*	*Hours*	*Demand (MW)*	*Wind (MW)*
1	934.04	156.20	13	1179.27	97.51
2	844.54	155.84	14	1200.43	86.2
3	779.24	157.14	15	1168.38	79.09
4	751.40	160.76	16	1189.85	71.93
5	734.17	162.06	17	1233.39	65.71
6	721.17	161.12	18	1375.51	60.93
7	766.22	160.73	19	1400	60.79
8	904.40	157.65	20	1340.73	63.64
9	1108.51	148.38	21	1289.94	71.95
10	1132.70	133.50	22	1237.62	95.16
11	1171.40	119.77	23	1124.54	118.51
12	1165.96	107.38	24	1038.06	123.78

Case 1: Without Wind Generator

The test system with 10 thermal units is taken from [19] the wind and load data is given in table VII, to illustrate the merits of the proposed method. Here 10% Operating Reserve is considered. Table VIII illustrates the Unit commitment of 10 generators without the integration of wind energy. The operating cost obtained in this case is $5,83,928.1.

TABLE VIII. UNIT COMMITMENT IN CASE 2

Units	Hours (1 to 24)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1-4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
6	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
7	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	0
8	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	0
9	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	0
10	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	1	0	0	0	0

Case 2: With a Wind Generator

The wind generator capacity considered to be 250MW for 10 unit system. The fuel cost of wind is considered to be negligible. The operating cost obtained in this case is $ 5,20,303.1. Table IX illustrates the Unit commitment of the 10 generators system along with wind with no Intermittency.

TABLE IX. UNIT COMMITMENT IN CASE 2

Units	Hours (1 to 24)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1-4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
6	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	1	1	1	1	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
8	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0
9	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	1	1	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Case 3: Ten-Unit Thermal System with a Wind Generator considering Intermittency

Along with case 2, Intermittency is considered in Wind generation, Reserve requirement is also considered in this case. Table X illustrates the Unit commitment of the 10 generators along with wind Intermittency modelled using Weibull PDF method. The cost obtained in this case is $5, 54,205.

TABLE X. UNIT COMMITMENT IN CASE 3

Units	Hours (1 to 24)																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1-4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
6	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	1	1	1	1	0	0
7	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0
8	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0
9	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	1	1	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table XI shows the comparison of operating cost in three cases, for 6 and 10 unit systems. As the model presented in this paper takes into consideration of wind intermittency the operating cost in case 3 is higher than that of case 2. Due reserve activation schedule the start-up cost can be reduced which is evident from Table XII.

TABLE XI. COMPARISON OF OPERATING COST

System	Operating cost		
	Case 1	*Case 2*	*Case 3*
6 Units	$ 22,432	$ 19,728.6	$ 23,663.75
10 Units	$ 5,83,928.1	$5,20,303.1	$5, 54,205.

TABLE XII. COMPARISON OF RESERVE COST

System	Unit Start-up cost ($)		
	Case 1	*Case 2*	*Case 3*
10 Units	3,800	7,280	2,280

VI. CONCLUSION

This paper presented a unit commitment solution to schedule the thermal generators with wind integration into the grid. In this paper intermittency in wind energy is also considered. Operating reserve requirement is obtained in all the cases. It is evident from the study that the operating reserve adjusts with the variability of wind, to optimize the net operating cost. Future work will include optimal provision of operating reserves in the face of wind integration challenges.

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